New subsurface mapping offshore southern West Greenland using geophysical and geological data

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The West Greenland continental margin has been the subject of petroleum exploration by companies and research projects since the 1970s and many data have been acquired since. Licensing rounds issued by the Greenland authorities in 2002 and 2004 offshore southern West Greenland resulted in company licenses which led to data acquisition and three exploration wells. The extensive new data form a basis for updated mapping by means of data, new analyses of the subsurface geology and improved understanding of the stratigraphy and the geological development. The Geological Survey of Denmark and Greenland (GEUS) has recently completed a comprehensive mapping project of the subsurface in an area covering 116 000 km^2 offshore southern West Greenland (Fig. 1). The results include maps displaying large structural highs and faults, Cretaceous sedimentary basins and volcanic areas, illustrated by cross-sections through the area. A new seismic stratigraphy with eight mega-units from the seabed to the basement was also defined. In addition, studies from wells of biostratigraphy and petrology were carried out that provide important new information. The new data include extensive 2D seismic data and eight wells including the three exploration wells AT2-1, AT7-1 and LF7-1 drilled in 2011 by Cairn Energy (Fig. 1). Key results of the work are summarised below.

Geological setting and scope of project

The southern West Greenland continental margin is located between West Greenland to the east and the oceanic crust and parts of the Davis Strait High to the west (Fig. 2). A number of rifted basins with large structural highs are interpreted to have developed offshore southern West Greenland during the Cretaceous (Chalmers *et al.* 1993; Sørensen 2006; Gregersen 2014). Cretaceous and Cenozoic sedimentary successions were previously defined from wells and outcrops on the central and southern West Greenland continental margin (Rolle 1985; Dam *et al.* 2009; Nøhr-Hansen *et al.* 2016). During the Paleocene and Eocene, oceanic crust developed between Canada and Greenland, and the Cretaceous rifted continental margin of West Greenland was separated from eastern Canada (Oakey & Chalmers 2012). The large-scale movements between Greenland and Canada generated new structures during the Palaeogene and reactivated faults within Cretaceous basins.

The purpose of the research-based project described here was to update previous subsurface mapping with the most recent data to provide an improved knowledge of the structures and the geological development, which can lead to an evaluation of the resource potential. The project was carried out in 2015–2017 for the Ministry of Mineral Resources in Nuuk and incorporated a number of sub-tasks including: (1) seismic interpretation and mapping; (2) well correlation; (3) biostratigraphy; (4) analyses of potential reservoir rocks in wells from 2011 and (5) analyses of igneous rocks, basement and provenance. This paper describes some of the key results from the seismic interpretation, mapping and well data-re-

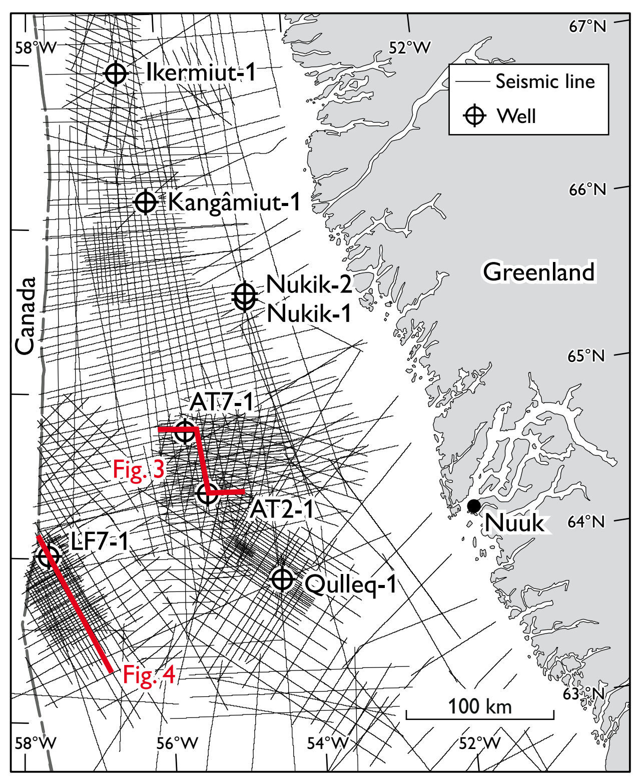


Fig. 1. Map of the study area offshore southern West Greenland with positions of 2D seismic lines and exploration wells. The positions of Figs 3 and 4 are also shown.

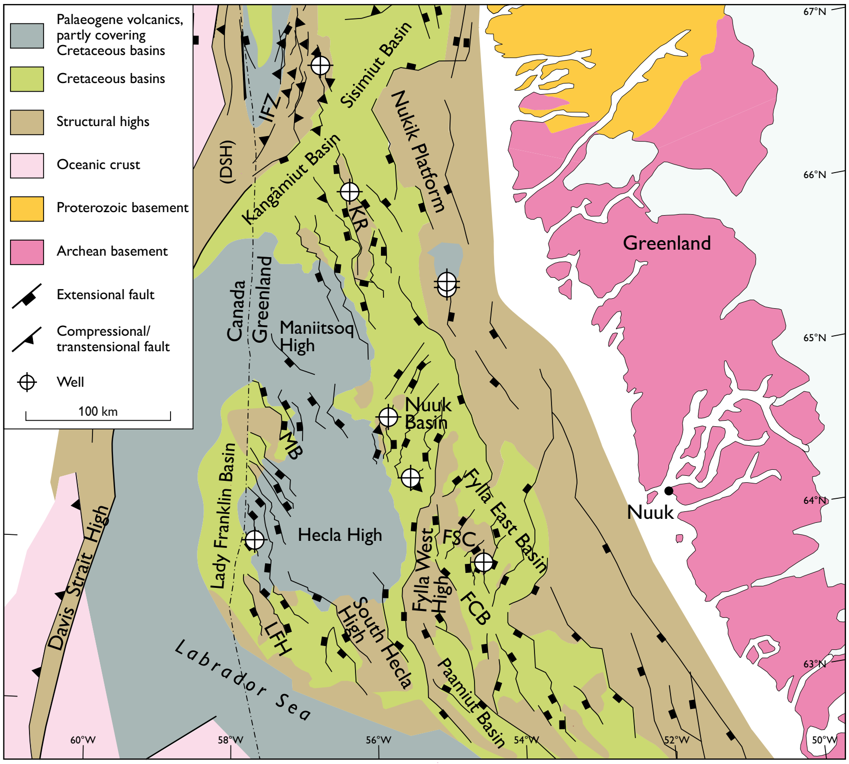


Fig. 2. Structural elements map of the southern West Greenland continental margin. The map shows areas with structural highs, faults, Cretaceous basins and Palaeogene volcanic cover. The majority of the large structures and faults trends towards the NW with a few towards the NE. In addition, the positions of the wells and the boundary to Canada are shown. **FSC**: Fylla Structural Complex with its composite structures, incl. **FCB**: Fylla Central Basin. **LFH**: Lady Franklin High. **MB**: Maniitsoq Basin. **KR**: Kangâmiut Ridge. **IFZ**: Ikermiut Fault Zone. Structural element names are mainly from Chalmers *et al.* (1993), Sørensen (2006) and Døssing (2011). The geological map of West Greenland onshore is from Henriksen *et al.* (2009). The position of the oceanic crust and the Davis Strait High in the Canadian sector are from Oakey & Chalmers (2012). The names of the wells are shown in Fig. 1.

lated tasks. The lateral extent of the main tectonic elements, including structural highs, faults and basins, is outlined in a structural elements map (Fig. 2).

Methods

Interpretation of seismic stratigraphic horizons and units was carried out using Schlumberger Petrel © software and included data from wells and seismic surveys (Fig. 1). In addition, other data including gravity and magnetic surveys and seabed sampling were used for the interpretation and mapping. Most structural highs and basins are defined and outlined by seismic interpretation in combination with gravity- and magnetic anomaly maps, and are supported by other data such as published refraction models. A number of methods were used at GEUS for the other studies, including scanning electron microscopy, porosity & permeability measurements, and rock/mineral analyses and radiometric dating using a laser ablation inductively coupled plasma mass spectrometer. Biostratigraphic dating based on palynology and micropalaeontology was carried out on a total of more than 200 samples from the AT2-1, AT-7-1 and LF7-1 wells.

Seismic stratigraphy and structures

A robust stratigraphic framework was established with eight seismic stratigraphic mega-units (A–H) divided by horizons from the seabed (A1) to the top of Pre-Cretaceous sedimentary rocks or the acoustic basement (H1) shown in Fig. 3. The mega-units include internal tops of sub-units (E2, Ev, F2, Fv and Hx) described below, and new biostratigraphy was used to constrain ages of the units. The units and most horizons are shown in seismic cross-sections across deep rifted basins separated by large structural highs (Figs 3, 4). Most of the structural highs, faults and basins trend SE–NW but a few strike in a more northerly direction or towards NE (Fig. 2). The total succession between the seabed and the basement has been mapped and shows thick basins between the main structures (Fig. 5), and also more local structures where the wells were drilled. Some basins and parts of basins are untested by wells.

Mega-unit H; Pre-Cretaceous basement

Mega-unit H includes the lower parts of basins and the basement of pre-Cretaceous ages (Fig. 3). It mostly includes the acoustic basement in large structures below the Cretaceous and Cenozoic basins, and was drilled in the AT7-1 and LF7-1 wells (Figs 3, 4). GEUS' analyses of igneous rock samples from lower parts of the AT7-1 well mainly reveal granites, granodiorites and tonalities. U-Pb dating of zircons from some of the samples gives ages of *c.* 2730–3190 Ma. The samples are from the lower part of mega-unit G and the uppermost part of mega-unit H in the drilled structure (Fig. 3) in a succession with interbedded sedimentary layers. Similar igneous rocks, some of which have been weathered, were also reported from the succession by Cairn Energy (2011). The rocks are mostly similar in age and composition to parts of the basement terrane in southern West Greenland. Metamorphic rocks reported by Cairn Energy (2011) from the lowermost part of the LF7-1 well occur just below the H1 horizon. However, pre-Cretaceous sedimentary rocks are also expected to be locally preserved in basins such as in the Sisimiut Basin (Fig. 2), where a sub-unit is present in the upper part of mega-unit H. Ordovician marine carbonates were sampled from the seabed over the Davis Strait High, where some possibly are *in situ* (Stouge *et al.* 2007). Such rocks may also occur in the adjacent basins. In addition, an organic-rich Ordovician sample from the Davis Strait was considered to have source rock potential (Bojesen-Koefoed 2011). Cretaceous and Paleocene oil seeps have been described from the Nuussuaq Basin farther north with a possible wider occurrence in West Greenland (Bojesen-Koefoed 2011).

Mega-unit G; Early to mid-Cretaceous

Large rift structures, local wedge-shaped units within mega-unit G and extensional faults developed during the Early to mid-Cretaceous (Figs 3, 4). Bowl or V-shaped, strong reflections near the G1 horizon (Fig. 3) are interpreted as sills of a larger sill complex in the Nuuk Basin and Lady Franklin Basin. Mega-unit G is most likely late Albian to Cenomanian in age. A seismic correlation (Fig. 3) with the AT7-1 well shows that the G1 surface divides a Cenomanian–Turonian sedimentary succession. The overlying lower part of mega-unit F is dominated by sandstones with conglomerates and thin claystones. The underlying mega-unit G includes a thick succession dominated by conglomerates and a lowermost ?late Albian – early Cenomanian succession including rocks from an igneous basement, interbedded thin sandstones, conglomerates and claystones. Lithologies in the AT2-1, AT7-1 and LF7-1 wells were determined by Cairn Energy (2011) and in this study.

Mega-unit F; Late Cretaceous – Paleocene

The present study shows that the lower succession of mega-unit F is mainly of Cenomanian–Turonian age. Variable reservoir properties were found from the study of well samples. In the lower part of mega-unit F of the AT7-1 well, the analysed conglomerate samples show intermediate to good reservoir quality, e.g. a sidewall core sample with 24.77% porosity and 78.73 mD permeability. The sandstones and overlying diatomite have high porosities, and medium to low and low permeability, respectively. The other Cretaceous rocks, analysed in the other two wells (AT2-1 and LF7-1), mostly show poorer reservoir quality. However, sandstones with reservoir potential are expected to be present in some of the structures. A 323 m thick succession dominated by sandstones of late Santonian age with reservoir potential is described from the lower part of the Qulleq-1 well in the Fylla Structural Complex (Christiansen *et al.* 2001; Fig. 2) and its top is also mapped in this study.

During parts of the Late Cretaceous, relative tectonic quiescence prevailed in most areas and thick claystone-dominated units were deposited in the basins. This study shows that parts of mega-unit F (Figs 3, 4) are dominated by thick Upper Cretaceous to Paleocene successions, which consist mostly of claystones. Such successions are drilled in the LF7-1, AT2-1, Qulleq-1 and Ikermiut-1 wells, which include the Ikermiut Fm (Rolle 1985). However, tectonic movements and erosion probably related to rifting and/or uplift may have occurred in the study area during Late Cretaceous to Paleocene, in some places indicated by truncation and faulting of structures (see also Chalmers *et al.* 1993). Erosion or non-deposition may also be indicated by missing sections in wells. Hiati of different timespans seem to occur during the Late Cretaceous to Early Paleocene (mostly from within the late Campanian to Danian) in the AT2-1 and AT7-1 wells (in AT7-1 even to the Coniacian), and were also previously noted in the Qulleq-1 and Ikermiut-1 wells (Nøhr-Hansen *et al.* 2016).

Volcanism

The lower parts of the AT2-1 well succession contain volcanic rocks and thin claystones, which are biostratigraphically dated in the present study as late Cenomanian to early Turonian. The horizon Fv correlates with the top of the volcanic succession which may partly cross or overlie mega-unit G (Fig. 3).

During the Paleocene–Eocene, flood basalts and other volcanic rocks were deposited in large parts of the West Greenland continental margin (Skaarup 2001; Sørensen 2006; Larsen *et al.* 2016). The tops of extensive volcanic areas and highs are mapped offshore southern West Greenland (Fig. 2) primarily from seismic reflection data at horizon Ev (Fig. 4) and from magnetic anomaly data. These volcanic areas include the Hecla High, the Maniitsoq High, the Davis Strait High and parts of the Nukik High (Fig. 2). The Nukik-2 well on the Nukik High includes a lower succession with hyaloclastite beds and thicker intrusives (dolerites), where the upper part has been biostratigraphically dated as Late Paleocene (Hald & Larsen 1987). An almost 700 m thick succession with Paleocene subaerial basaltic lava flows was drilled in the lower

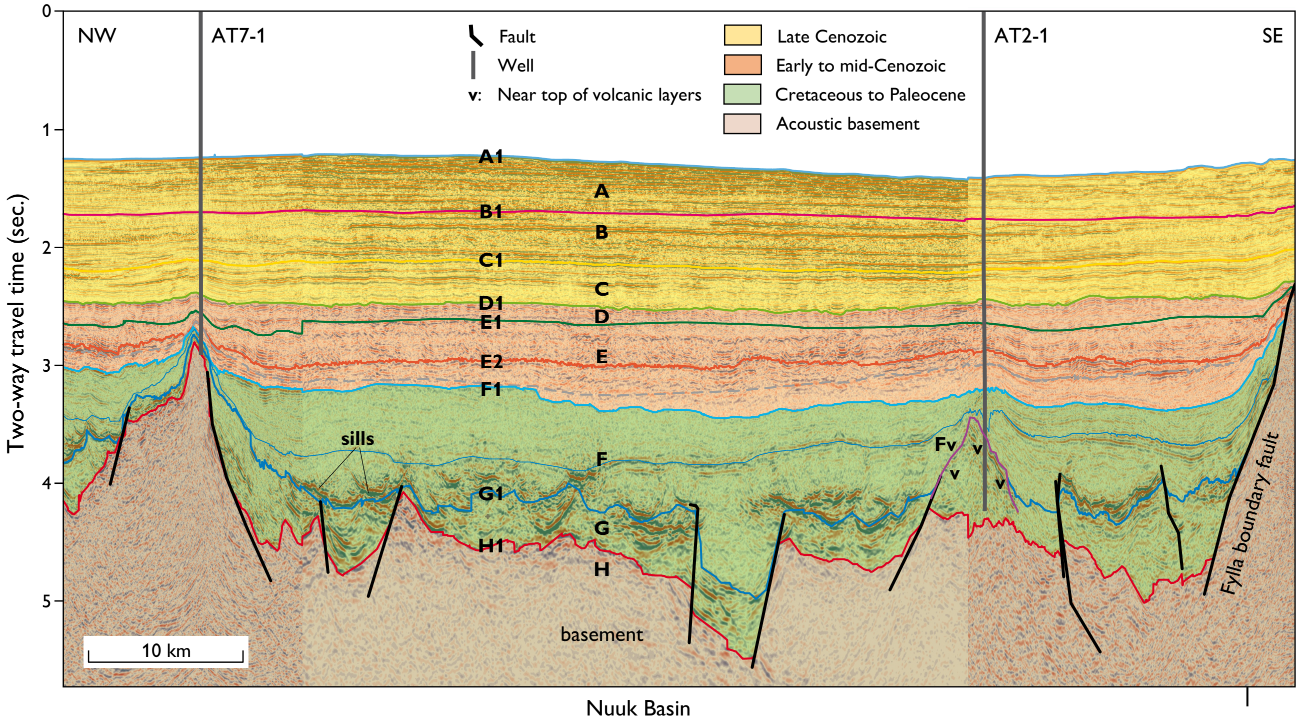


Fig. 3. Composite NW–SE seismic section across the Nuuk Basin with large structures and the AT2-1 and AT7-1 wells. The succession from the seabed to the basement is divided by seismic stratigraphic horizons A1–H1 into seismic mega-units A–H and tentative ages (maximum timespans) of major successions are shown in colour. The deeper parts of the section are dominated by a Cretaceous sedimentary succession with rifted basins, and with a local volcanic succession and sills. The seismic lines shown (TGS-GREEN2003-29, TGS-GR2000-215 and ENC2005-1) are courtesy of TGS-NOPEC Geophysical Company ASA. The location of the section is shown in Fig. 1.

part of the Hellefisk-1 well (Hald & Larsen 1987) north of the study area. Paleocene basalts were sampled from the seabed over the Davis Strait High and south of the Hecla High, where additional Early Eocene basalts were recovered (Larsen & Dalhoff 2006). A refraction seismic study by Funck *et al.* (2007) also shows basalts in the western parts of the study area and farther west with a tie to the Canadian Gjoa G-37 well. This well includes basalts with thinner mudstones in a >1 km thick Danian to Thanetian interval (Nøhr-Hansen *et al.* 2016). The Palaeogene volcanic rocks mostly cover parts of structures and Cretaceous sedimentary basins in the study area (Figs 2, 4), in parts of the Davis Strait – southern Baffin Bay areas (Gregersen & Bidstrup 2008) and in the Nuussuaq Basin (Dam *et al.* 2009; Larsen *et al.* 2016). The top of the volcanic successions (Ev) is overlain by the seismic horizon E2 of Late Paleocene age (late Thanetian from Nøhr-Hansen *et al.* 2016) towards the south (Fig. 4).

Geological development of younger units

The West Greenland continental margin moved towards NE and N in connection with the Palaeogene sea-floor spreading between Canada and Greenland (Oakey & Chalmers 2012). These movements caused compression–transtension tectonism with thrust faults and associated basins along the Davis Strait High and the Ikermiut Fault Zone during the Late Paleocene to Eocene (Fig. 2; Gregersen & Bidstrup 2008). Seismic geometries in mega-units E and D with irregular sub-units near faults and basin mounds suggest mass-flows including slumps and basin fans (Fig. 3). They were formed during mainly the Eocene and Miocene and may include potential leads for hydrocarbon. Parts of the mass-flows may be related to movements during the formation of Palaeogene oceanic crust. Parts of upper Eocene, Oligocene and lower Miocene successions are mostly absent in wells from the area (Nøhr-Hansen *et al.* 2016). The upper parts of mega-unit D and mega-unit C are Miocene in age, mega-unit B is possibly Late Miocene to Pliocene and mega-unit A is probably Late Pliocene to Pleistocene in age (Fig. 3). The ages of the mega-units are indicated from biostratigraphy (Piasecki 2003; Nøhr-Hansen *et al.* 2016). In Miocene to Pleistocene successions, fewer large faults and other indications of tectonism are found. Large contourite drifts, slides and other forms of mass-mobilisation developed during the Miocene to Pleistocene (Nielsen *et al.* 2011) within mega-units A–C (Fig. 4). In addition, S- and SW-directed shelf progradation occurred,

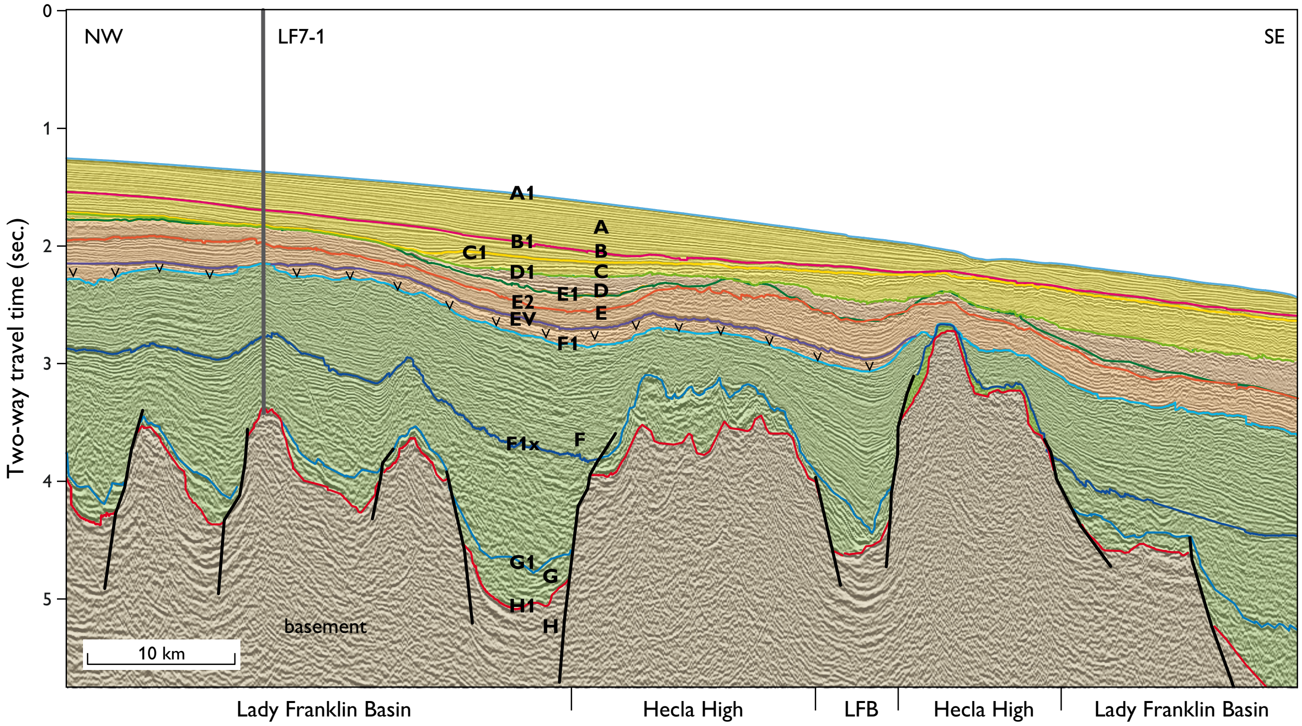
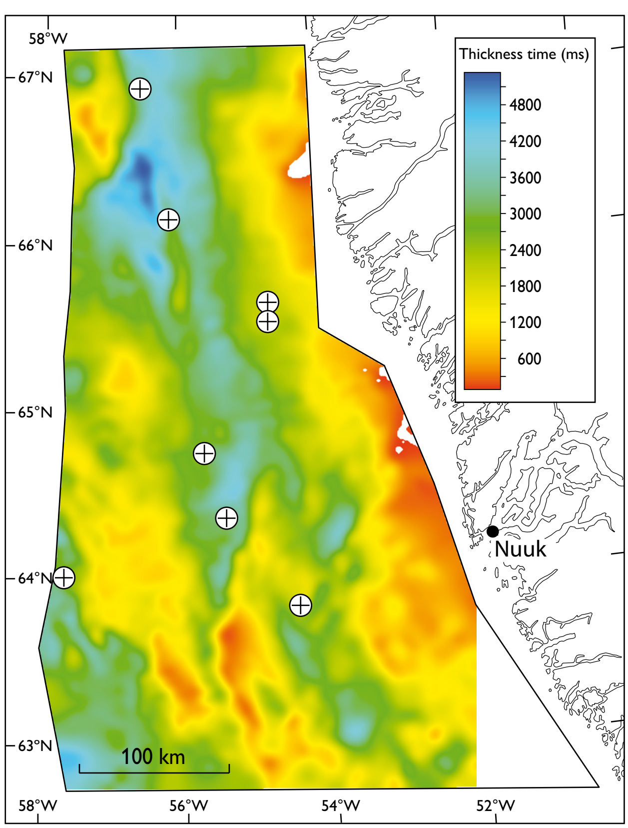


Fig. 4. The LF7-1 well and a composite NW–SE seismic section across the Lady Franklin Basin. The succession from the seabed to the basement is divided by seismic stratigraphic horizons A1–H1 into seismic mega-units A–H and tentative ages of major successions are shown in colour (Fig. 3). It is dominated by Cretaceous successions of mega-units F and G and includes rifted structures. Mega-unit F is overlain by a probably thin Palaeogene volcanic succession. A Miocene–Pliocene contourite succession of mega-units B and C occurs south-east of the LF7-1 well. The seismic line shown (TGS-BLF2005-43) is courtesy of TGS-NOPEC Geophysical Company ASA. The location of the section is shown in Fig. 1.



probably as a result of glaciations, and a near-horizontal succession also formed in mega-unit A.

Conclusions

A study was carried out with subsurface mapping using geophysical and well data offshore southern West Greenland. A seismic stratigraphy with eight mega-units (A–H) from the seabed to the pre-Cretaceous basement has been defined in the area and shown on cross-sections. A new structural elements map displaying the main structures, basins and faults, as well as a sedimentary thickness map are presented.

Fig. 5. Thickness isochore map in two-way travel time (ms) between the seabed (A1 horizon) and the Pre-Cretaceous basement (H1 horizon). The map includes mostly sedimentary successions but locally also includes volcanic successions as illustrated in Figs 2–4. Thick dominantly sedimentary successions occur in mainly the Lady Franklin Basin, the Fylla East Basin, the Nuuk Basin, the Kangâmiut Basin and the Sisimiut Basin, whereas successions thin over structural highs (Figs 2–4). The names of the wells are shown in Fig. 1.

Biostratigraphic ages, radiometric dating and lithologies from well data are correlated to parts of the mega-units. The studied wells comprise Cretaceous to Cenozoic sedimentary successions, a volcanic succession and granitic rocks from the basement. The results presented here are based on analyses from this study and recently released data from the wells drilled in 2011 by Cairn Energy (AT2-1, AT7-1 and LF7-1). The results have improved the understanding and outline of the large-scale structures, basins and provide input for further work in the region including new resource-potential evaluations, but also point out uncertainties and risks that require clarification.

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